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Low Power dc Arcjet Operation With Hydrogen/Nitrogen Propellant Mixtures

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LOW POWER dc ARCJET OPERATION WITH HYDROGEN/NITROGEN PROPELLANT MIXTURES

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Abstract

The arcjet assembly from a flight model system was modified with a new thoriated tungsten nozzle insert and has been tested with hydrogen-nitrogen mixtures simulating the decomposition products of ammonia and hydrazine. Arcjet power consumption ranged from 0.7 to 1.15 kW depending on flow rate, input current, and mixture composition.

At a nominal 1 kW power level the ammonia mixtures thrust efficiency was about 0.31 at specific impulse values ranging between 460 and 500 sec. Hydrazine mixtures gave similar thrust efficiencies at the same power level with specific impulse values between 395 and 430 sec.

Large, spontaneous voltage mode changes were not observed once the thruster had passed a period of instability immediately following start up. This period of instability, and the startup at low pressure, were seen as major causes of constrictor damage during the tests.

Introduction

The development of arcjet thrusters for use in space propulsion was the goal of a large scale research effort begun in the mid 1950's and continued into the early 1960's. A comprehensive review of this early work was conducted by Wallner and Czika[1] in 1965. During this period, power levels between 1 and 200 kW were considered but most of the research was concentrated at the 30 kW level[2-5] assuming both the availability of nuclear electric power sources and missions requiring primary propulsion.[6] Recently, interest in arcjets as propulsion devices has once again grown to a point where significant R and D programs have been established both in government and industry. At present the focus of the NASA research effort is on the design of a thruster capable of operating on storable propellants (e.g., NH_3, N_2H_4) at low powers (i.e., 0.5 to 1.2 kW). This is due both to the increase in specific impulse thought to be attainable with arcjets as compared to electrothermal thrusters now in use (100 sec or greater increase) and to the power realistically available to auxiliary propulsion on operational satellites. The state-of-the-art carried over from the previous programs at low power levels includes the technology base generated by the Plasmadyne Corporation (later Giannini Scientific Corp) in two separate government sponsored programs.[7-9] In one of these[7,8] a 1-kW flight system was designed for testing in the Space Electric Rocket Test (SERT) program. The design goal was 24 min of unattended operation with hydrogen as propellant. Although this flight never materialized the thruster did undergo an extensive test program at NASA Lewis Research Center in 1962 in which efficiencies of 10 to 30 percent were obtained at specific impulses values between 600 and 1400 sec. In these tests erosion of the anode-nozzle was found to be significant and the thrust measurements, from which performance was deduced, were deemed unreliable. The other program[9] produced a 2 kW arcjet that was operated for 150 hr with hydrogen. The test data showed a specific impulse value of about 920 sec at a 30 percent efficiency level. The test was voluntarily terminated and examination showed that the electrode erosion was not severe. Propellants other than hydrogen were used with the 1 kW thruster[8] with umpromising results as severe electrode erosion problems were encountered.

More recently, a 1-kW thruster left over from the SERT program has been tested at NASA Lewis.[10] These tests confirmed the performance data of the 1960's trials. Once again initial erosion of the anode was observed but stopped after a certain point allowing reasonably consistent long term operation. Perhaps more encouraging was the finding that hydrogen-nitrogen gas mixtures simulating ammonia decomposition products ran with specific impulses of over 400 sec and efficiency levels near 30 percent.

This report described further operation of the Plasmadyne 1 kW assembly modified with a new nozzle/anode insert. This thruster was tested over a range of power levels and propellant flow rates with hydrogen-nitrogen mixtures simulating both ammonia and hydrazine decomposition products. The major goals of this research were: (1) to determine whether or not the modified unit could be operated consistantly without slipping into the more destructive low mode described in the earlier study; (2) to extend the data base for low power dc arcjets of the conventional design and; (3) to study the causes of performance deterioration for direction in further tests. As such it represents an intermediate step toward the overall program goal of developing a reliable, efficient low power arcjet.

Apparatus

A photograph of the Plasmadyne thruster system as originally designed for the SERT flight test is shown in Fig. 1. Design details can be found in Ref. 7. From this system the cathode/anode arcjet assembly was removed, modified and used in the test described herein. A cross-sectional schematic of this is shown in Fig. 2. The cathode was a 3.2 mm diameter, 2 percent thoriated tungsten rod held within a 7.8 mm o.d. molybdenum tube. Clearance was provided around the cathode rod to permit some regenerative cooling by a split off portion of the propellant flow. The remaining portion of the

propellant flowed through helical grooves on the outside surface of the molybdenum tube providing swirling gas between the tube and its boron nitride housing. The original design utilized metal K-seals to prevent gas leakage. These were found to deform upon repeated disassembly and reassembly of the unit. To alleviate this problem the sealing flange perifery was ground to a conical surface to seat on the mating boron nitride surface. With this modification, the pressure check described in Ref. 10 indicated a leak rate of approximately 3×10^{-6} kg/sec of nitrogen gas at ambient temperatures and a presource differential of 3.8×10^{5} Pa. This led to an estimated leakage of 2.4 percent at normal operating temperatures and pressures.

Since only slight modifications were made for these tests (described below) this estimate is deemed reasonable of the experiments described.

The dimensions of the original insert, designed to fit the anode housing with a self sealing taper, are shown in Fig. 3(a). The original tungsten nozzle insert had a 0.23 mm throat diameter that diverged to 1.27 mm at the exit plane to give a start-of-test area ratio of 30. As stated in Ref. 10, the constrictor diameter quickly eroded to a final, stable dimension estimated at approximately 0.79 mm. For the test described herein, the original insert was replaced by a new insert machined from 2 percent thoriated tungsten stock. The chamber side of this insert was similar to the original but the constrictor was 0.64 mm in diameter and 1.14 mm in length. This constrictor diameter was found to be effective in stabilizing the operation of an arcjet simulator, run on nitrogen at similar current levels, in a previous study.[11] Figure 3(b) shows the details of this insert. The diverging side of the nozzle was trumpet shaped with a final half-angle of 35°. The final expansion ratio was 56. During the course of testing two nozzle extensions were used. The first was the extension made from HBN grade boron nitride for the tests described in Ref. 10. This also had a 35° half-angle and provided a final expansion ratio of 3300. The second was made from HBR grade boron nitride but otherwise was identical to the first.

Both boron nitride grades are hot pressed with a boric acid binder; calcium is added to the HBR grade to stabilize the binder and raise its melting point. Both extensions were attached with the tantalum straps described in Ref. 10. In that report the anode insert alone was referred to as the "short nozzle" configuration and the insert/boron nitride extension combination as the "extended nozzle" configuration. This nomenclature will be continued in this report with the addition of HBN and HBR to distinguish between the two grades of boron nitride used for the extension. A longstanding problem in low power arcjets has been the measurement of the pressure in the chamber. In most cases, including earlier, unmodified Plasmadyne designs, the reading was simply taken at the inlet to the thruster housing. This introduces a significant error as it does not account for pressure drops in internal propellant feed passages. To better define the thrust chamber pressure, a tap was machined into the molybdinum chamber housing 1 in. from the front face. A stainless steel fitting was modified to accept a copper conical seal for use as the coupler. This was found to be leak tight even under full power conditions with the thruster running at steady state. A pressure tap to the arc chamber was then possible, avoiding the small feed lines so the pressure measurements presented should be an accurate representation of the true values.

Power Systems

For the majority of the tests described in this report, a conventional dc power supply rated for 400 V at 25 A was used in combination with a variable ballast resistance. Two 1 mH inductors in series were also included in the circuit. The pulse width modulated source[12] used in the earlier study[10] could not supply the voltage necessary to sustain operation in the desired mode with the modified insert and so was tried only briefly. Work on a modified version with a wider operating envelope is in progress.[13]

Instrumentation

Thrust measurement. The thrust measurement system was described in detail in Ref. 10. Briefly, the thruster was mounted on a thermally isolated rectangular platform supported by four flexure plates. A strain gage force transducer rated for a full scale force of 1.47 N was used to measure the applied thrust. A 5 V dc excitation source was used to produce force transducer output signals of approximately 1.02 V/N. Calibration was accomplished using weights suspended on monofilament line and attached to a windlass. A total of 16 g could be used in 4 g increments. These weights could be added at any point during the testing.

Even with the thermal isolation and water cooling discribed in Ref. 10 a small thermal drift in the zero thrust signal was observed. The zero point was reestablished periodically and the drift was compensated for as described in the following Procedures section.

Flow control and metering. The flow control and metering system was designed to allow use of hydrogen, nitrogen or mixtures of the two. Commercially available flow meters employing thermal conductivity type sensors were used throughout the experiments. These had a full scale range of 5 SLM and were rated as accurate to 1 percent of full scale. Bellows-sealed valves were used for shut off to eliminate leakage and fine adjustments were made with precision needle valves in each propellant line. Complete propellant shutoff could be achieved using a single valve in the final line to the thruster. This feature was utilized both in the starting sequence and in the zero drift correction procedure.

Data recording. An eight channel strip chart recorder with a 0 to 150 Hz bandwidth was used to record the arc current and voltage readings, the thrust measurements, the propellant flow rates, and the background pressure of the test cell. The arc chamber pressure (from the point as described in the previous section) was taken manually from a Bourdon type pressure gage with a 2500 torr full scale reading. The temperature on the outside surface of the molybdenum anode housing was monitored using a K-type thermocouple, this data was also taken by hand.

Power metering. - Power to the arcjet was measured by monitoring the arcjet voltage and current. The voltage measurement was taken across the anode

and cathode feed on the bell jar flange. The current was sensed with a Hall-effect current probe. The output of this was fed both to the strip chart recorder and to a 50 MHz ociloscope. As the arcjet was operated isolated from the building ground, an isolation amplifier was employed in the voltage measuring line between the bell jar flange and the recorder.

Vacuum Facility

The facility used in all experiments was the 1.5 m diameter by 5 m long vacuum chamber. For a more complete discription see Ref. 10. With no propellant flow the background pressure could be maintained at approximately $7x10^{-4}$ Pa ($5x10^{-6}$ torr). Under typical operating conditions, i.e., full mass flow and power to the thruster the background pressure rose to the 0.013 to 0.13 Pa (10^{-4} to 10^{-3}) torr range. A prior publication on ambient pressure effects on thrust measurements of low Reynolds number nozzles (2200 to 12 000) indicated that an ambient-to-chamber pressure ratio of 10^{-3} was sufficient to avoid viscous effects.[14] Since Reynolds numbers in the low power arcjet are probably less than 1000 a more rigorous criterion was used. Only measurements taken with a tank pressure below 0.13 pa (10^{-3} torr) were considered valid in data reduction.

The pressure in the arc chamber, with the arcjet in operation, was always greater than $2x10^{-5}$ Pa (1500 torr) so an ambient-to-chamber pressure ratio of at least 10^{-7} was always maintained. While the choice of this criterion is judgemental and somewhat arbitrary, as the effects of background pressure on arcjet thrust measurements have not been fully documented, it should be noted that thrust measurement errors due to high ambient background pressure lead to underestimations in performance values.

Experimental Procedure

A routine procedure was followed prior to operation of the arcjet in any test. Once the electronics and cooling water had been turned on a 45 min waiting period was allowed to assure thermal equilibrium. Before power was applied to the thruster the thrust measurement was calibrated as described in an earlier section. This was followed by a measurement of the cold flow thrust generated by each of the gas mixtures to be used in the testing. In addition to providing the cold-flow specific impulse used in calculation of efficiency, this also allowed comparison between tests.

The maximum power supply voltage (400 V) would not cause breakdown at the operating level of mass flow. To start the arc the propellant flow was brought to the desired value and the power supply turned on. Once the power supply voltage reached its maximum value, the final shutoff value in the flow system was closed and the pressure allowed to drop to a level where Paschen breakdown occurred. As soon as current flow was observed the propellant valve was reopened so the propellant flow could rise to the preset levels. As the arcjet structure heated up, the flow rates had to be adjusted manually to compensate for the changing chamber pressure.

In each test the thruster was run until a steady state temperature on the anode housing was observed. The time required for this varied with test conditions but was in the neighborhood of 20 min. Performance values were calculated from data taken after this thermal equilibrium was attained. Typically, the thruster was run to steady state, measurements were taken and then both power and propellant were shutoff to reestablish the thrust zero. In almost every case there was a slight offset that remained constant for quite some time after shutdown so this value was simply substracted from the steady state thrust measurement.

Results and Discussion

Operating characteristics and observed phenomena common to all the tests (i.e., with and without nozzle extensions) will be discussed in the first part of this section. This discussion will include the major comparisons of the performance and condition between the modified thruster and the original design as related in an earlier report. Both cold and hot flow data will then be presented to relate the efficiency of each nozzle design. In the last part of the section the results of an extended test of a mixture simulating hydrazine decomposition products will be discussed.

Appendix A lists the terms, definitions, and equations used in the calculations presented in this report.

Operating Characteristics and Phenomina

Initial tests. In each of the first two thruster trials gas leaks appeared as the arcjet temperature rose. Although no performance data were taken from these tests, the observed phenomena are reported here in order to fully document the units operational history. In one of these tests a normal starting sequence, described in the next section, was followed by stable operation with a propellant mixture simulating the decomposition products of ammonia at a total mass flow rate of about $27x10^{-6}$ kg/sec. The chamber pressure and anode housing temperature rose with time until the temperature reached 450 °C (approximately two-thirds of the way to the steady state temperature found in later tests). At this point the chamber pressure peaked and began to decline. The thrust measurement exhibited similar behavior. Both tests were terminated soon after this point to prevent damage to internal thruster components. After both tests the thruster was disassembled and damaged internal seals were replaced. The thruster did not leak during the next, and subsequent, testing and so was not removed from the thrust stand again until the conclusion of testing.

Starting. In previous reports argon has been used to avoid difficult starts.[10,11] In these tests the transition to the propellant of choice was accomplished after the arc had been established at the desired current level. As this option will likely not be available on commercial spacecraft it was not used in the tests performed for this report. Rather, as stated in a previous section, the thruster was started by throttling the flow and so allowing the chamber pressure to drop until the open circuit voltage of the power supply was sufficient to cause breakdown. In all but one of

the tests the arcjet was started with the power supply current setting at 10 A. Although each starting record was unique, a number of similar phenomena stood out. First, a current spike was recorded at the start of every test. Before stable operation was obtained a period of instability was always observed during which the current and voltage traces both displayed large variations. This period was characterized by a flickering, intermittent plume and some sparks from the nozzle, phenomena observed also in earlier tests even with argon as the working fluid.[10,11] A typical starting sequence, taken from the first test, is shown in Fig. 4. Here, the instability persists for about 20 sec at which point a momentarily stable period is observed at a voltage well below the final operating level. After this the arc voltage once again becomes unstable until, after approximately 1 min, a final, quiescent state is reached. This behavior indicates the following sequence of events. After the propellant flow is shutoff the chamber pressure drops until breakdown occurs between the cathode and the chamber side of the anode. As the propellant flow is reintroduced the point of anode attachment, a spot since it is seating in a high pressure region, moves up and down the constrictors length causing the variation in voltage. In the stable period in which the thrusters operated at low voltage (~15 sec at 60 V) the arc anode foot point had moved back upstream to seat on the chamberside. After this the spot once again begins its rapid motion along the constrictor until, finally, the flow field and arc reach a stable condition with the major region of anode attachment in the diverging section of the nozzle (designated the high mode to be discussed in the next section). Many starts did not include the stable period spent in the low voltage mode and were accomplish in less time. An example is shown in Fig. 5(a). This is also an example of a restart, i.e., start up after a run and before the thruster had cooled completely. In general, this type of start was easier than were cold starts but this was not true in every case. Figure 5(b) shows the most difficult start observed in the tests. Here, the current level was initially set at 8 A. In this test the instability persisted for an extended period and after about 100 sec the current level was raised to 10 A. Finally, after nearly 4 min had passed, stable operation was achieved.

The significance of the observations described above is better understood when viewed with performance data and a description of the final condition of the thruster. As such further discussion will be saved for a following section.

Modes of operation. As previously reported,[10] the low power arcjet can operate in two distinct voltage regimes, referred to as the low and high modes. In the low voltage mode the arc attaches upstream of the constrictor. In this high pressure region it was felt that this attachment occurred as a constricted spot. In the high voltage mode the arc extended through the constrictor to seat in the diverging section of the nozzle. This mode may be characterized by a diffuse, rather than spot attachment zone. In the tests reported herein, with a thruster having a significantly longer constrictor, the low voltage mode was not observed once the period of instability, see following section on startup, was passed. Rather, once past the initial instability, the arcjet ran smoothly with minor voltage fluctations typically 2 to 4 V in magnitude at the 10 A current level. These fluctuations occurred abruptly rather than as smooth transitions. Each fluctuation was visually observed to be accompanied by a rotation of the luminous plume generated by the arcjet although there was no evidence of a single, spotlike attachment point. This behavior implies that the major current carrying area in the nozzle can rotate with up or downstream motion near the constrictor exit. At any given current level the rate of incidence of these voltage excursions would vary with no obvious pattern. As the current level was decreased the overall average rate of incidence of the voltage fluctuations was seen to increase as were the total (highest-to-lowest) voltage levels. This is illustrated in Fig. 6. In the test from which these chart recordings were taken the current was changed from 10 to 6 A with all other conditions held constant with a 2:1 hydrogen to nitrogen mixture at a mass flow rate of 36.5×10^{-6} kg/sec. Although the actual cause of the voltage fluctuations is unknown at present, it is possible that it is related to the irregular shape of the constrictor exit caused by erosion at startup.

Voltage-current characteristics. Shown in Fig. 7 are the current-voltage characteristics from two tests, one taken using a 3:1 hydrogen to nitrogen ratio and the other a 2:1 ratio. A number of points from each current level are shown to illustrate the scatter observed. The voltage levels shown for the 3:1 mixture (simulating ammonia) are close to those taken at a slightly higher propellant flow rate in the previous test with the unmodified thruster.[10]

Figure 8 illustrates the relationship of voltage to mass flow rate at a constant current level (~10 A). Once again, values taken from varying voltage levels are presented. Two trends can be seen. First, the ammonia mixtures run at higher voltage levels that the mixtures designed to simulate hydrazine. This result was expected as the higher proportion of hydrogen leads to more efficient transfer of energy away from the arc core necessitating the higher sustaining voltage. In these tests the magnitude of voltage fluctuation decreased with increasing flow rate which would seem to indicate a more stable arc. The actual recorder trace, however, shows that the rate of incidence in the voltage fluctuations increases dramatically at the higher flow rate. Their appearance also changes as the fluctuation at the higher mass flow rate appears only as a spike with no time spent at the lower level. This is illustrated in Fig. 9.

Performance

A total operating time in excess of 14 hr was accumulated on the modified thruster with propellant mixtures simulating hydrazine or ammonia decomposition products. These hours were spread over eleven separate test periods. Through the middle of the sixth test (approximately 8 hr) reasonably reproducible data were obtained and no major changes in performance were observed. In the middle of the sixth test a restart was accompanied by an extended period of instability (>2 min). In the next test period the 8 A start was attempted in which the period of instability persisted for more than 4 min. Performance values decreased at this point. The change in characteristics was abrupt and was then followed by the remaining 6 hr

of testing during which no further significant reduction in performance was noticed. These observations combined with others, indicate performance degradation may be due mainly to constrictor erosion at startup. This point will be returned to in the next section after the final thruster condition has been described. It should be noted that this deterioration involved a decrease in efficiency from the 30 to the 25 percent level and did not represent a catastrophic failure of the arcjet.

In this section only data taken in the first six tests will be presented. Data taken after the difficult start in test six is presented to show how the operating characteristics vary with current using mixtures simulating hydrazine and to show extended operation with the realization that some performance limiting damage had occurred.

Cold flow measurements. Room temperature gas mixtures were used to evaluate the nozzle efficiency with no power applied to the arcjet. As the newly machined pressure tap was downstream of the restrictions caused by the cathode flow passages, the cathode was left in place for these readings. In a series of tests with no nozzle extension, chamber pressure was found to be linearly dependent on mass flow rate for both 2:1 and 3:1 mixtures of hydrogen and nitrogen. This is shown in Fig. 10(a).

Assuming an accurate force and chamber pressure measurement, the product of the thrust coefficient, C_F, and the minimum throat area, A^*, can be obtained from

$$F = C_F P A^*$$

These values are shown in Fig. 10(b). To obtain an accurate value of C_F from this the mimimum throat area is needed. The cold flow data presented here were taken after a number of hours of operation and a number of startups so some erosion of the original throat dimension would be expected. Examination of the orifice at the end of testing showed the orifice to have lost its cylindrical shape indicating no even, predictable erosion mechanism so precise determination of throat area at any point during testing was not possible. Still, at the end of testing a 0.64 mm diameter drill could not be passed through the constrictor. Shown in Fig. 10(c) are values of C_F versus mass flow rate for a range of A^*. The lowest value in each set was calculated assuming a 20 percent increase in the original radius of the throat, the middle value assumes a 10 percent increase and the highest value assumes the original radius. Using a ratio of specific heats, k, of 1.4 the maximum value of C_F attainable is 1.8. For comparison, in the original tests with the unmodified anode,[10] thrust coefficients in the 1.3 to 1.4 range were calculated from data taken after the throat had eroded to the extent that the expansion ratio was less than 3. From this, the plot shown in Fig. 10(c), and the condition of the throat at the end of testing it appears that while assuming no throat erosion is unreasonable. The values obtained assuming a 10 percent radius increase are too low.

Powered arcjet operation. In one extended test the effect of mass flow rate on performance was studied at a constant current (10 A) for both 2:1 and 3:1 hydrogen to nitrogen ratios. The effect of current variation was also studied for the 3:1 mixture ratio in this test. The total test duration was approximately 2.5 hr with power and mass flow shutdowns at about 40 min intervals for a rezero of the thrust measurement. As discussed in a previous section, an equilibration period was allowed between each parametric variation with raw data reduction only after thermal equilibrium was restored. Where possible, points near the high and low performance limits are shown to illustrate the variation that could be expected from this thruster system. The average performance lies near the median between the high and low values.

In Fig. 11 arc power, specific impulse and efficiency are plotted versus mass flow rate for both 2:1 and 3:1 hydrogen to nitrogen mixtures. The most obvious feature in the plot is the highly scattered data at the lowest flow rate for each mixture. The fluctuations in voltage observed were greatest at the lower flow rates and this gave rise to large variations in both specific impulse and efficiency. As the flow rate was increased in magnitude past 28×10^{-6} kg/sec the fluctuations decreased. Further increases in mass flow had less of an effect especially in the case of the 2:1 mixture simulating hydrazine. For the simulated NH_3 mixture specific impulses in the 460 to 500 sec range were obtained consistantly with the data scatter precluding any real trends. For the N_2H_4 mixtures the specific impulse varied from a low of 410 to a high of 480 sec. While arcjet power consumption increased steadily with mass flow for this mixture, the I_{sp} values declined to a minimum at about 36.5×10^{-6} kg/sec and then rose back to the 420 level although the measurement uncertainty was not sufficient to show this as a trend and further increases in mass flow rate raised the ambient pressure in the tank to unacceptable levels. There was no discernible trend between voltage level and either specific impulse or efficiency at fixed mass flow and current. It should be noted that the performance variations were not large except at the lower flow rates and that these tests took place before any of the difficult starts occurred. To compare the performance of the modified thruster with that obtained using the original design,[10] tests were performed using a 3:1 hydrogen to nitrogen mixture at a fixed mass flow rate and varying current levels. The results are shown in Fig. 12. Arc power is seen to increase with arc current in approximately a linear fashion over the small range of currents studied. Specific impulse also increased significantly with current; the value of 503 sec was the highest obtained in any test at 10 A. In the previous report, values of arc power and specific impulse of 850 to 950 W and 400 to 430 sec, respectively, were found at mass flow rates 10 to 20 percent above those used to obtain the data in Fig. 12. Other tests performed at the 10 A current level with mass flow rates equal to and above those used in the previous report (refer to Fig. 11) produces specific impulse values in the 460 to 480 range with none below 460 sec. All of these tests were performed with no nozzle extension. At these elevated flow rates the thruster ran at power levels between 980 and 1140 W. In both this and the previous report efficiences obtained at 10 A were near 31 percent.

The increased specific impulse values obtained with the modified thruster result from the longer narrower constrictor which provided a better heating zone. The similar efficiences obtained in the tests indicates that thrusters of this design suffer frozen flow losses that are highly current dependent and indicate a highly peaked enthalpy profile across the nozzle exit not amenable to equilibrium calculations.

In a later test performed with the HBR grade nozzle extension in place the 6 to 12 A current range was studied with a 2:1 mixture at a mass flow rate found previously to produce stable operation (i.e, 36.5x10^{-6} kg/sec). The results are shown in Fig. 13. As with the data from the 3:1 mixture tests, the arc power was found to be roughly linear with current (slope approximately 62 W/A). Again efficiency decreased and specific impulse increased with increasing current. Included on the plot are some data taken at the 10 A level and with the short nozzle for comparison. These values are extremely close to the data taken with the extended nozzle in place and before the difficult start (data also appear in graph). This implies that a simple nozzle extension may not be effective in increasing nozzle efficiency under hot flow conditions.

The data described above were taken during an extended (1 hr 45 min) test of the 2:1 mixture. During the first part of this test the current and mass flow rate were held constant and the thruster was run past the point where steady state housing temperature and chamber pressure were obtained. The results of this part of the test are shown on the left hand side of Fig. 14. The startup for this test was relatively mild and the voltage level was seen to rise over the first 5 min or so. After this point the typical fluctuations set in although the overall average voltage did decrease with time. Specific impulse averaged close to 420 sec and voltage fluctuations lead to I_{sp} changes. At 8 min a particularly high value (>440 sec) was obtained. While this change in I_{sp} value was accompanied by a voltage increase, the change did not appear to warrant the magnitude of the jump. No other indications of changes in operating parameters were present so this point is considered valid though a presently unexplainable anomoly. The chamber pressure reached its steady state value in between 5 and 8 min while the housing temperature required 15 to 20 min to reach 95 percent of its maximum value.

After the 35 min test period the thruster power and propellant supplies were shutoff and the thrust zero reset. The thruster was allowed to cool for about 20 min to assure no further zero drift. The following startup was particularly difficult with nearly 2 min being required for stable voltage levels. The thruster was then allowed to reestablish thermal equilibrium at 10 A before the variation in current was performed. During this period the thruster reattained the chamber pressure, housing temperature, and voltage level of the first part of the test but there was a noticable drop in efficiency (approximately 4 percent) indicating some damage to the constriction may have occurred during the long startup. The arcjet ran stably through the remainder of the test.

Thruster condition. There was a thorough examination of the thruster at the end of testing. At the exit of the throat, in the diverging section of the nozzle, small globules of molten metal were observed. This is a common observation after tests with arcs through narrow constrictors and has been observed even with water cooled anodes.[11] After these were removed the diverging side of the anode piece was seen to have maintained its integrity. A photograph of the nozzle is shown in Fig. 15(a). The converging side, pictured in Fig. 15(b), was blackened and small molten dots were in evidence. These conditions are indicative of arc anode spot attachment inside the chamber. As mentioned previously the constrictor had lost its original circular shape. The irregular shape seen in both figures indicates that the erosion did not take place in an even, continuous fashion, but rather along what appeared to be troughs. This, taken with the observations presented in previous sections, suggest that most of the constrictor erosion occurs at startup and in the accompanying unstable period when the arc foot is moving in and out of the constrictor. This would account for all of the observed phenomena including the variation in voltage, performance degradation after hard starts and the molten material in the anode nozzle with no evidence of loss of material in this region. It would also explain why no significant degradation in performance was observed in the life test of the 2 kW Plasmadyne thruster.[9] In this test a single start was followed by 150 hr of continuous running so the rigors of the multiples starts necessary for the station keeping application were avoided. The strong implication is that a faster "softer" starting procedure should be employed to reduce this type of damage. To this end, a program has been initiated to employ a high voltage, low total power pulse to start the arcjet at full flow and at a controlled current level to avoid the initial spike.

The difference in the condition of the two nozzle extensions was extreme. Figure 16(a) and (b) document this difference. In each, the darkened extension on the left is the one made from the HBN grade material. Binder material that has bled from the main body is obvious in each photograph. The HBR grade extension, shown on the right in each figure, maintained its original smooth white appearance with the exception of a slight darkening near the base of the diverging section. This is believed to be tungsten from the arcjet. During the testing the HBR grade extension was subjected to numerous thermal cycles form room temperature to thermal equilibrium with the arcjet with no apparent cracks, melting, or erosion.

Concluding Remarks

Several conclusions can be drawn from the data presented in this report. First, operation of the modified thruster in the desired high voltage mode on propellant mixtures simulating hydrazine and ammonia decomposition products was demonstrated at power levels currently available to auxiliary propulsion on operational satellites (0.7 to 1.1 kV). With ammonia mixtures, specific impulses in the 440 to 500 sec range were routine. These values are significantly higher than those found with the unmodified thruster as reported

previously.[10] This can be attributed directly to the fact that the constrictor used in these tests did not erode as badly as did the insert used in the unmodified thruster. The hydrazine mixtures give specific impulse values in the range of 370 to 440 sec. In both of the above cases the ranges were obtained by varying the current and/or the mass flow rate. Also, for both propellant mixtures increasing arc current had the effect of increasing the specific impulse and decreasing the efficiency of the device. These trends are expected for any arcjet design involving a constricted arc and so can be used in systems level tradeoffs to tailor a specific system for most efficient use of available power and propellant. For both mixtures overall stability of operating characteristics (voltage and thrust) decreased at the lower values of current and mass flow rate.

The observations and data indicate that much of the damage to the constrictor was done at startup and in the ensuring period of instability. This suggests both that a well designed power processor and starting procedure may be necessary to reduce this damage to an acceptable level and that the description for a reliable arcjet system must include an appropriate power processing unit.

Appendix A

Arcjet Performance

The conventional symbols and equations used in evaluating arcjet performance are set forth herein for convenience with a minimum of explanatory detail.

A^* nozzle throat area, m^2

C_F thrust coefficient

F thrust, Newton

g gravitational acceleration, 9.8 m/sec^2

h,c subscripts denoting hot and cold conditions

I_{sp} specific impulse, sec

I'_{sp} theoretical specific impulse, sec

k ratio of specific heats

M.W. molecular weight, kg/Kmol

$\dot{m}$ mass flow rate, kg/sec

P pressure, Pa

P_a arc power, W

v exhaust velocity, m/sec

η thrust efficiency

$$= \frac{\frac{1}{2}\dot{m}v_h^2}{P_a + \frac{1}{2}\dot{m}v_c^2} \qquad \text{(A1)}$$

$$= \frac{I_{sph}^2}{\frac{2}{g^2}\frac{P_a}{\dot{m}} + I_{spc}^2} \qquad \text{(A2)}$$

REFERENCES

1. Wallner, L.E. and Czika, J., Jr., "Arc-Jet Thrustor for Space Propulsion," NASA TN D-2868, 1965.

2. John, R.R., Connors, J.F., and Bennett, S., "Thirty Day Endurance Test of a 30 KW ArcJet Engine," AIAA Paper 63-274, June 1963.

3. John, R.R., "Thirty Kilowatt Plasmajet Rocket-Engine Development," Avco Corp., Wilmington, MA, RAD-TR-4-6, July 1964, (NASA CR-54044).

4. Todd, J.P. and Sheets, R.E., "Development of a Regeneratively Cooled 30-KW Arc Jet Engine," AIAA Journal, Vol. 3, No. 1, Jan. 1965, pp. 122-126.

5. Todd, J.P., "30 KW Arc-Jet Thrustor Research," Giannini Scientific Corp., APL-TDR-64-58, Mar. 1964.

6. "Arc-Jet Application Study," General Electric Co., Cincinnati, OH, Sept. 1961, (NASA CR-140076).

7. Ducati, A.C., Humpal, H., Meltzer, J., Muehlberger, E., Todd, J.P., and Waltzer, H., "1-KW Arc Jet-Engine System-Performance Test," Journal of Spacecraft, Vol. 1, No. 3, May-June 1964, pp. 327-332.

8. Greco, R.V., and Stoner, W.A., "Development of a Plasmajet Rocket Engine for Attitude Control," Plasmadyne Corp., GRC-1341-A, Dec. 1961.

9. McCaughey, O.J., Geideman, W.A., Jr., and Muller, K., "Research and Advanced Development of a 2 KW Arc-Jet Thrustor," Plasmadyne Corp. Santa Ana, CA, GRC-1646, 1963, (NASA CR-54035).

10. Nakanishi, S., "Performance Evaluation of a 1 KW Arc Jet Thruster," AIAA Paper 85-2033, Oct. 1985.

11. Curran, F.M., "An Experimental Study of Energy Loss Mechanisms and Efficiency Considerations in the Low Power dc Arc-Jet," AIAA Paper 85-2017, Oct. 1985.

12. Gruber, R.P., "Power Electronics for a 1 KW Arc-Jet Thruster," AIAA Paper 86-1507 to be presented at the 22and Joint Propulsion Conference, Huntsville, AL, June 16-18, 1986.

13. Gruber, R.P.: Private discussions. NASA Lewis Research Center, Cleveland, OH.

14. Sovey, J.S., Penko, P.F., Grisnik, S.P., and Whalen, M.V., "Vacuum Chamber Pressure Effects on Thrust Measurements of Low Reynolds Number Nozzles," NASA TM-86955, 1985.

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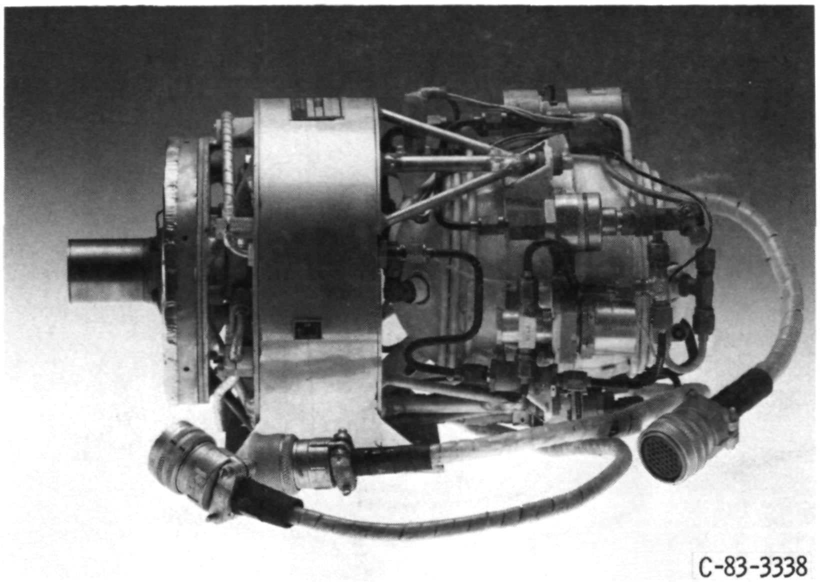


Figure 1. - Plasmadyne 1 kW arcjet thruster flight system.

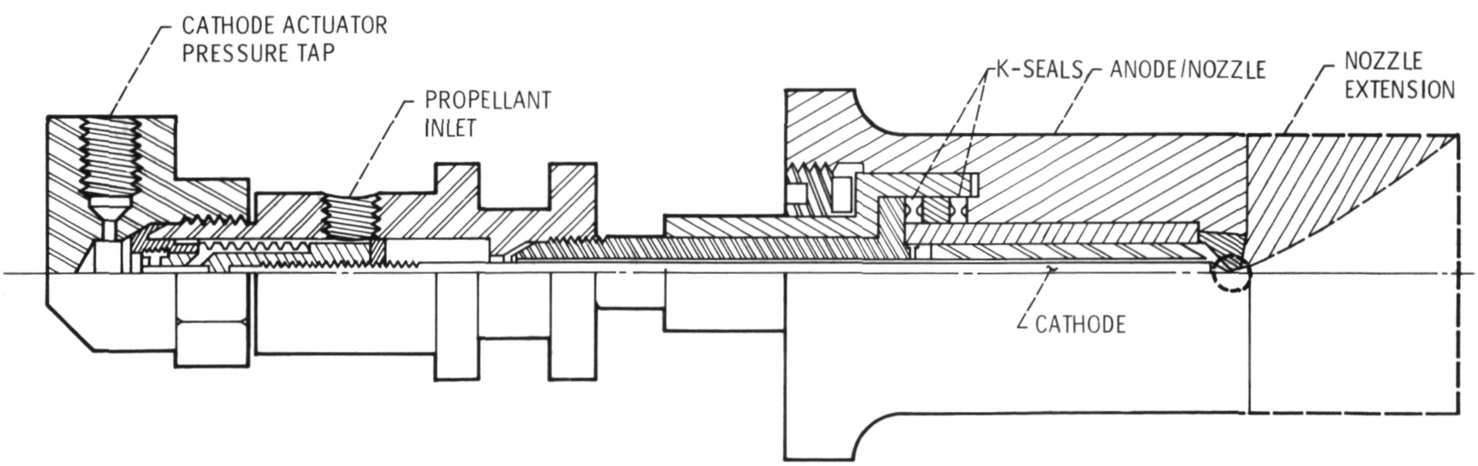
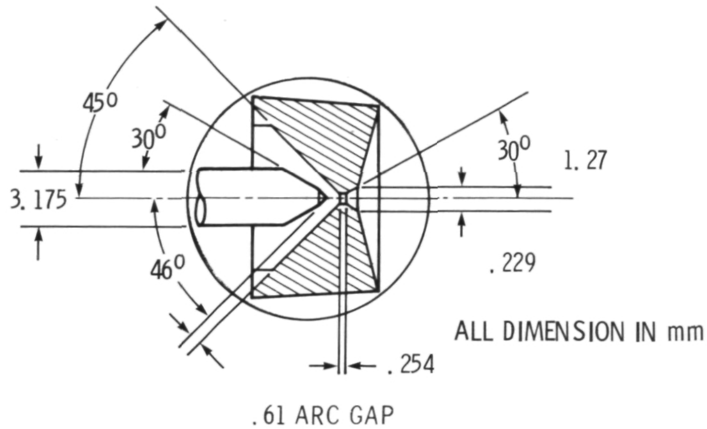
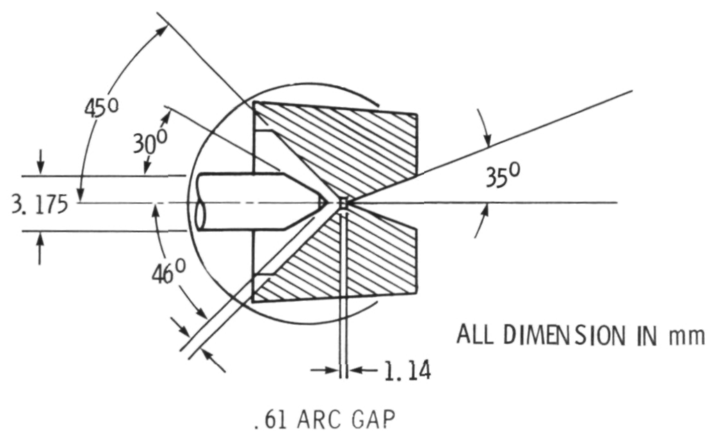


Figure 2. - Cross-section view of the cathode-anode structure and nozzle extension.



(a) Original insert.



(b) Modified insert.

Figure 3. - Schematic of nozzle inserts and internal dimensions (cutaway).

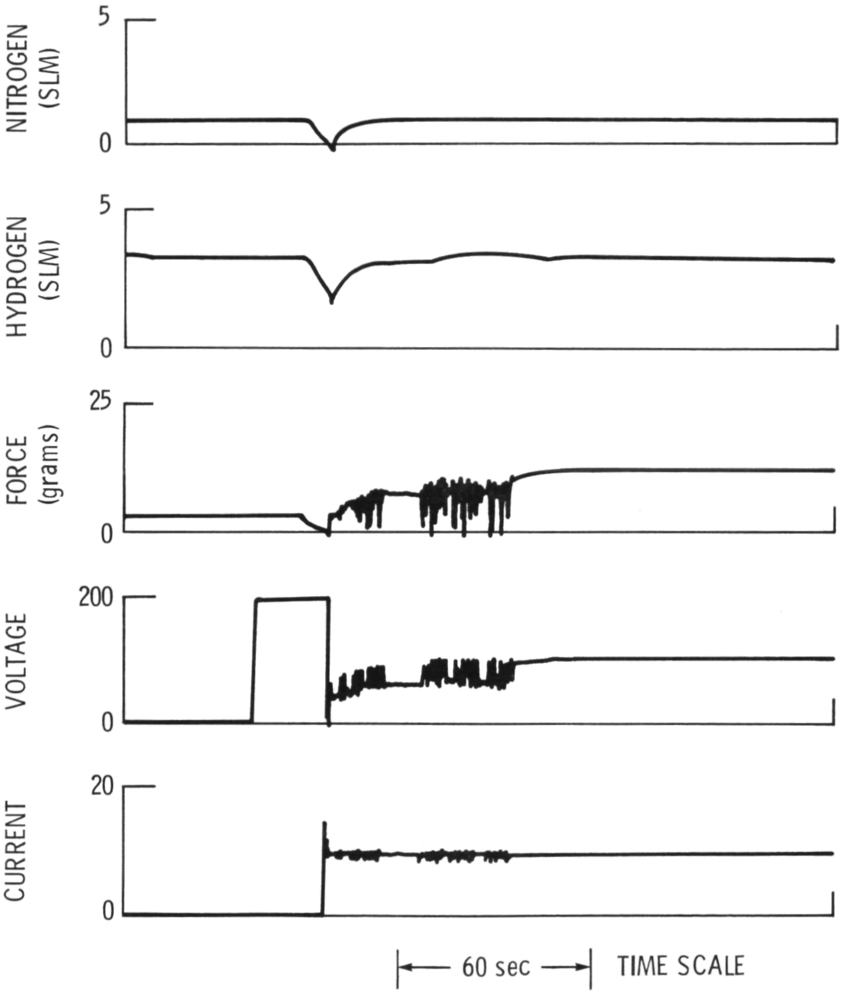
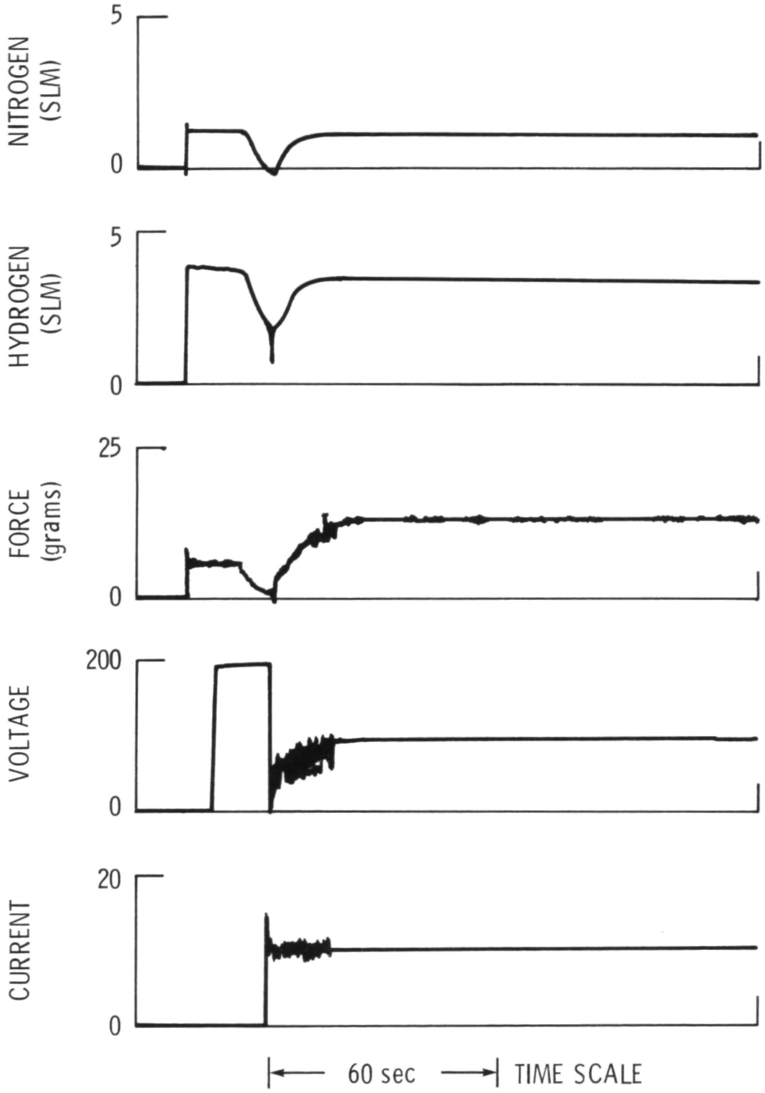
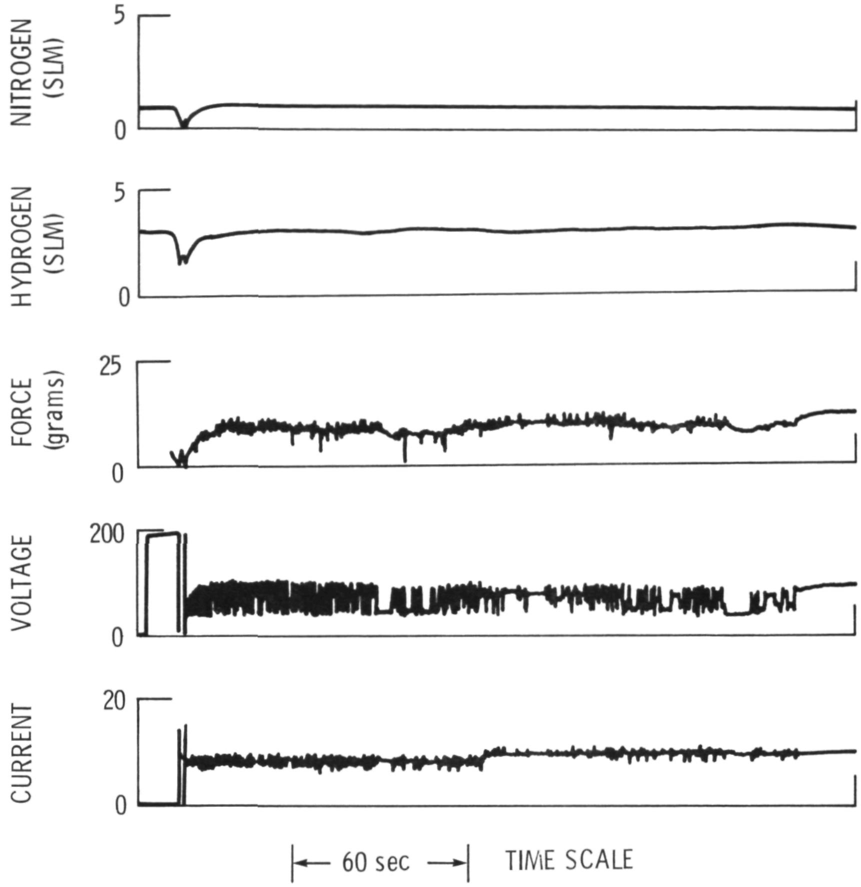


Figure 4. - Chart recording of initial arc starting sequence.



(a) Hot start.

Figure 5. - Strip chart record of attempted start.



(b) Attempted start at 8 A.

Figure 5. - Concluded.

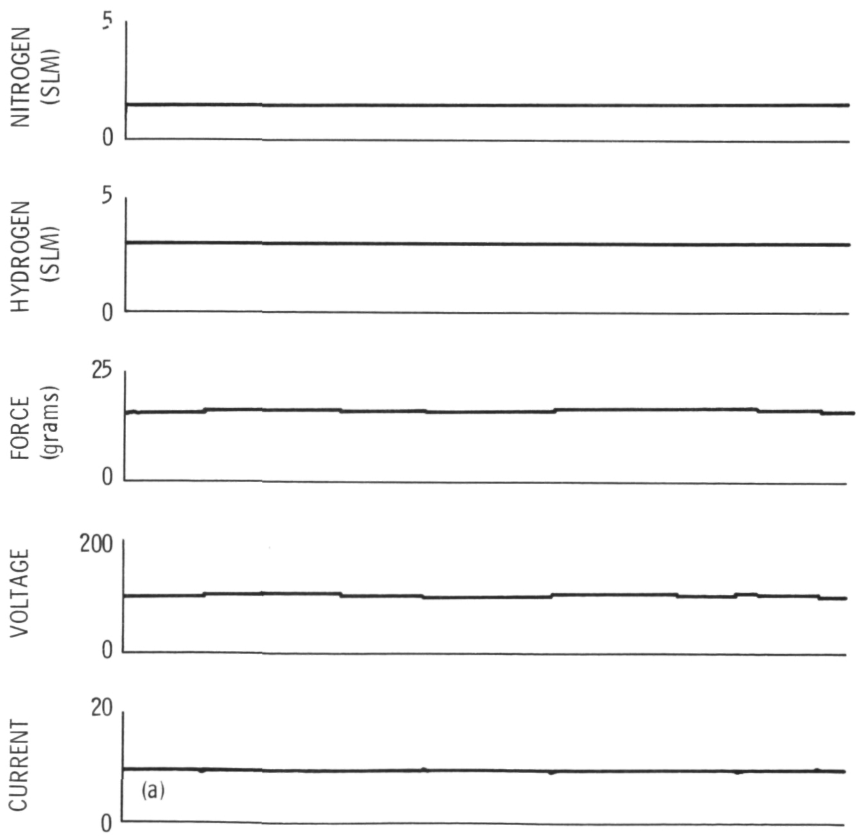


Figure 6. - Typical voltage fluctuations at 10 amps (~1000 watts).

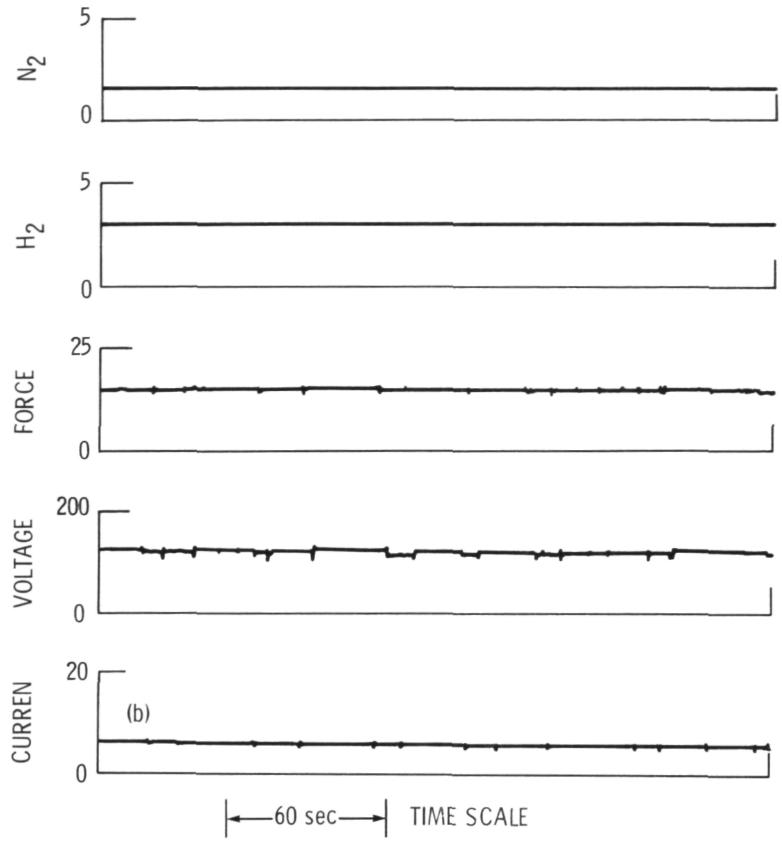


Figure 6. - Concluded.

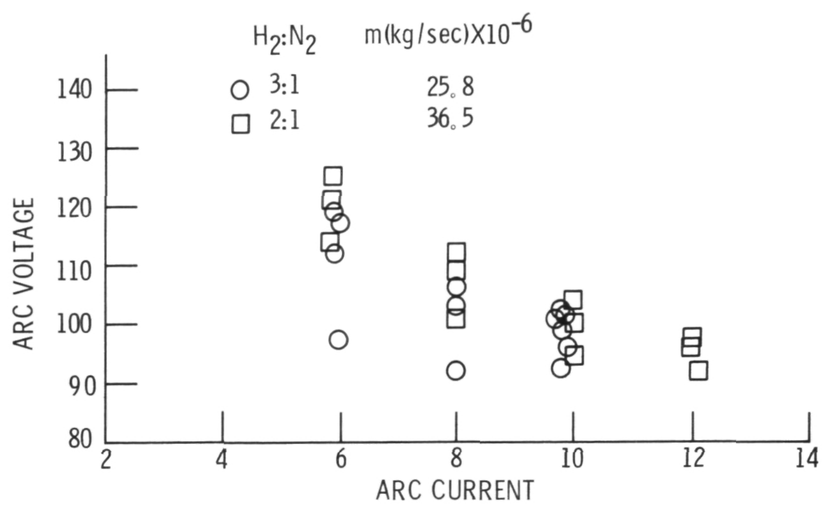


Figure 7. - Current-voltage characteristics from selected tests.

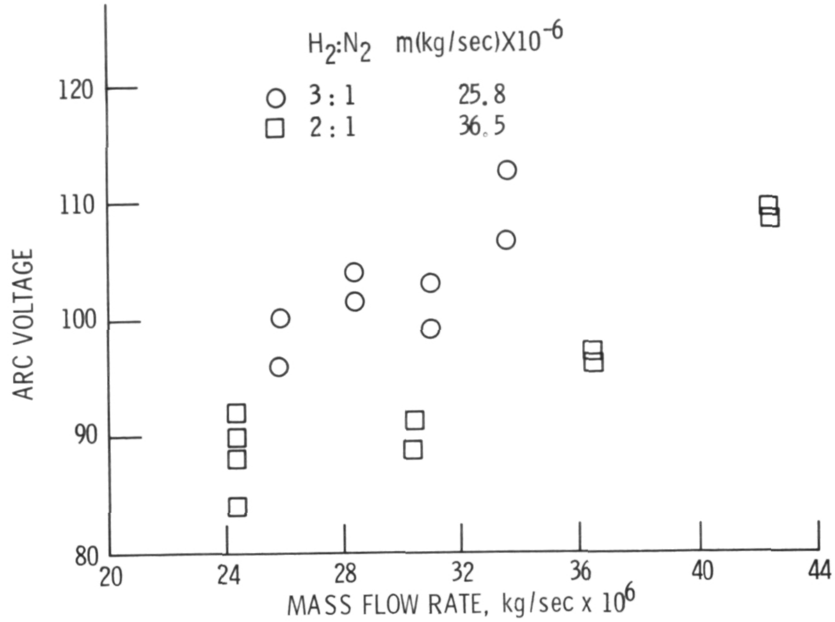


Figure 8. - Arc voltage versus mass flow rate at a constant current.

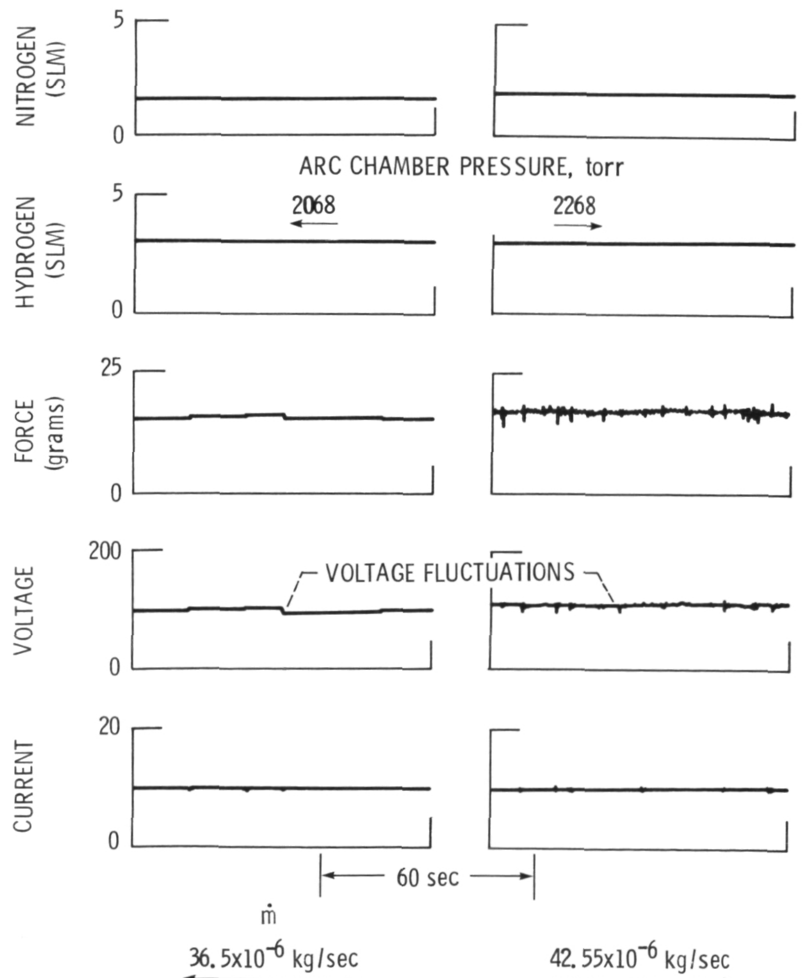


Figure 9. - Chart records of voltage fluctuations at differing mass flow rates.

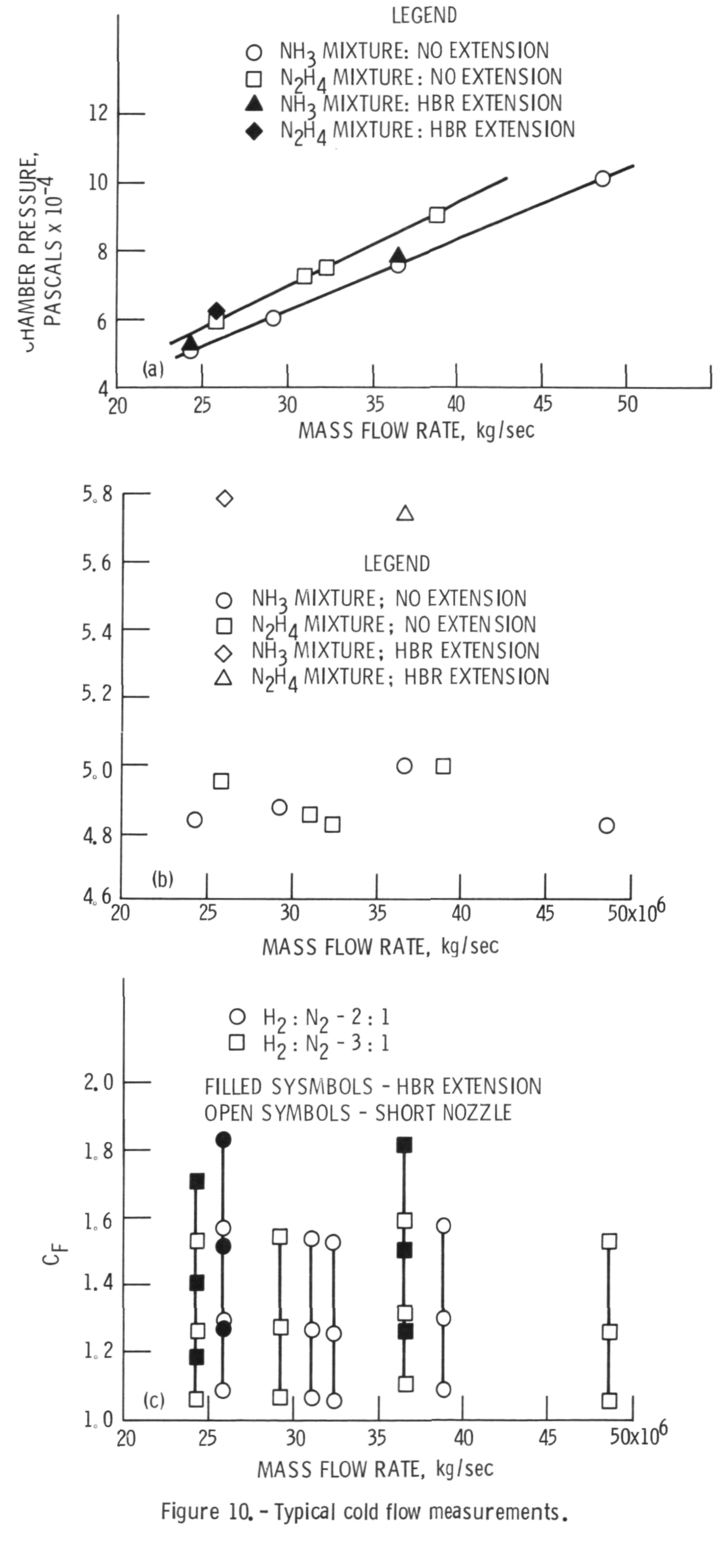


Figure 10. - Typical cold flow measurements.

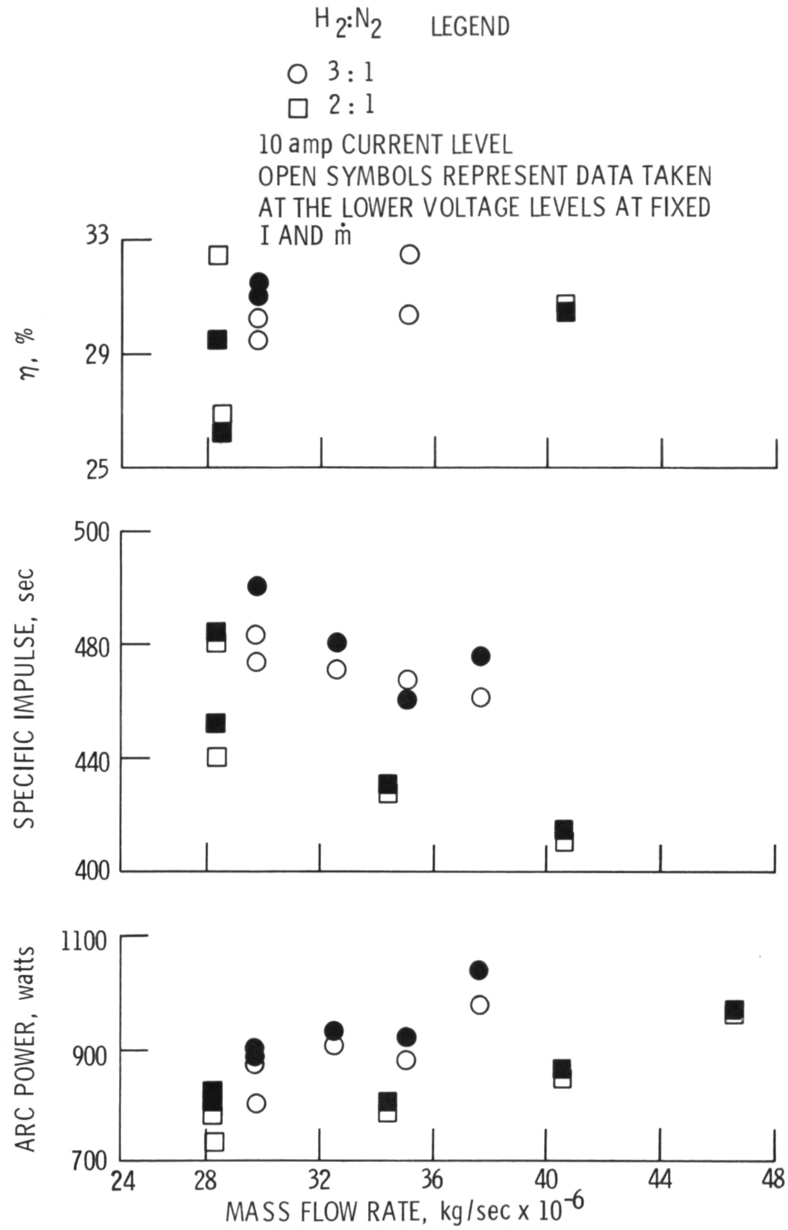


Figure 11. - Arc power, specific impulse and efficiency versus mass flow rate.

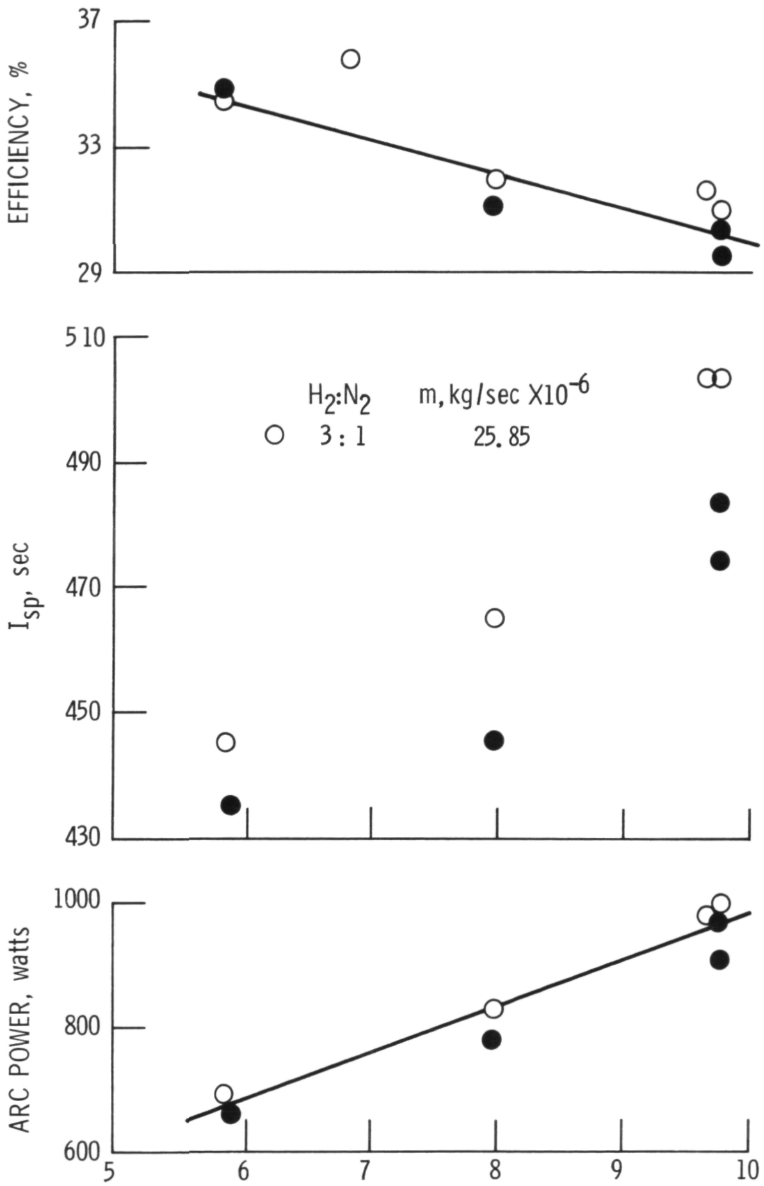


Figure 12. - Arc power, specific impulse and thrust efficiency versus current.

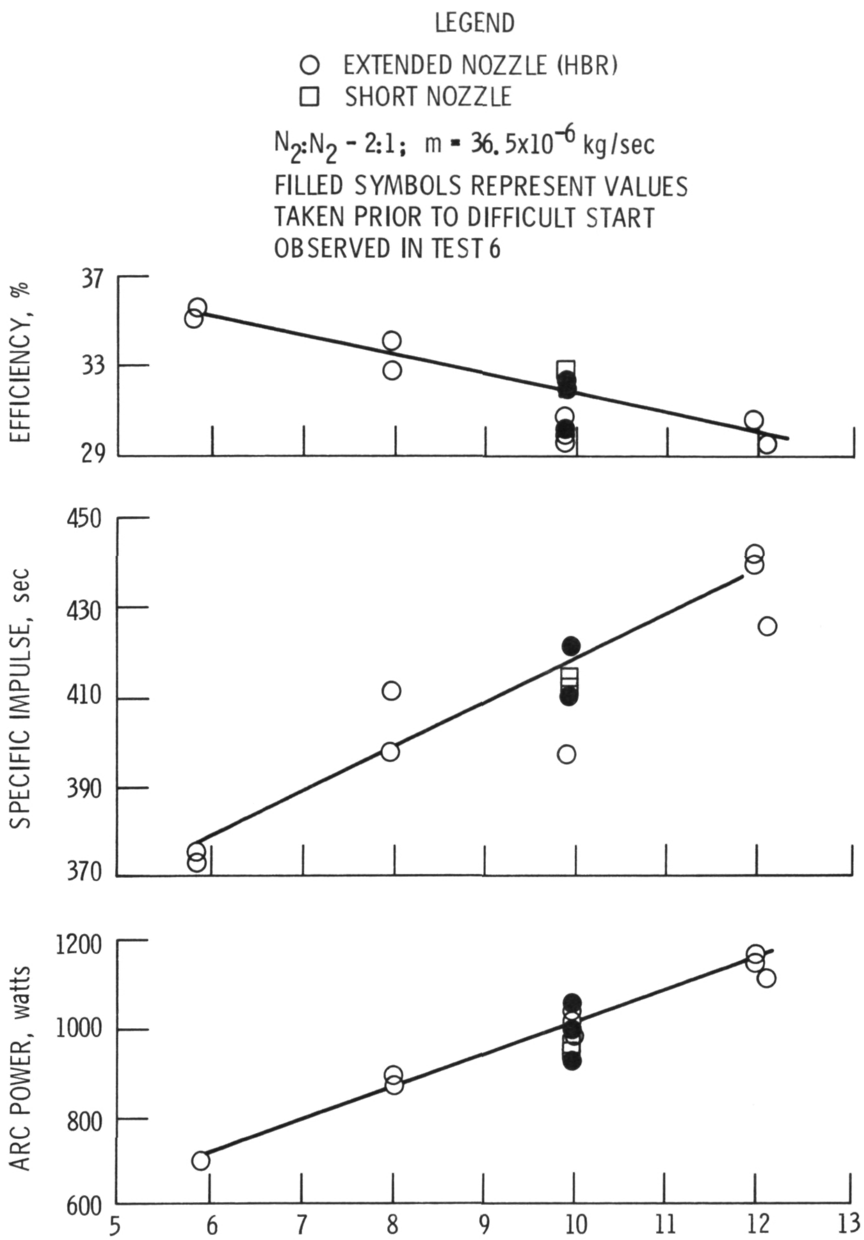


Figure 13. - Arc power, specific impulse and thrust efficiency versus current.

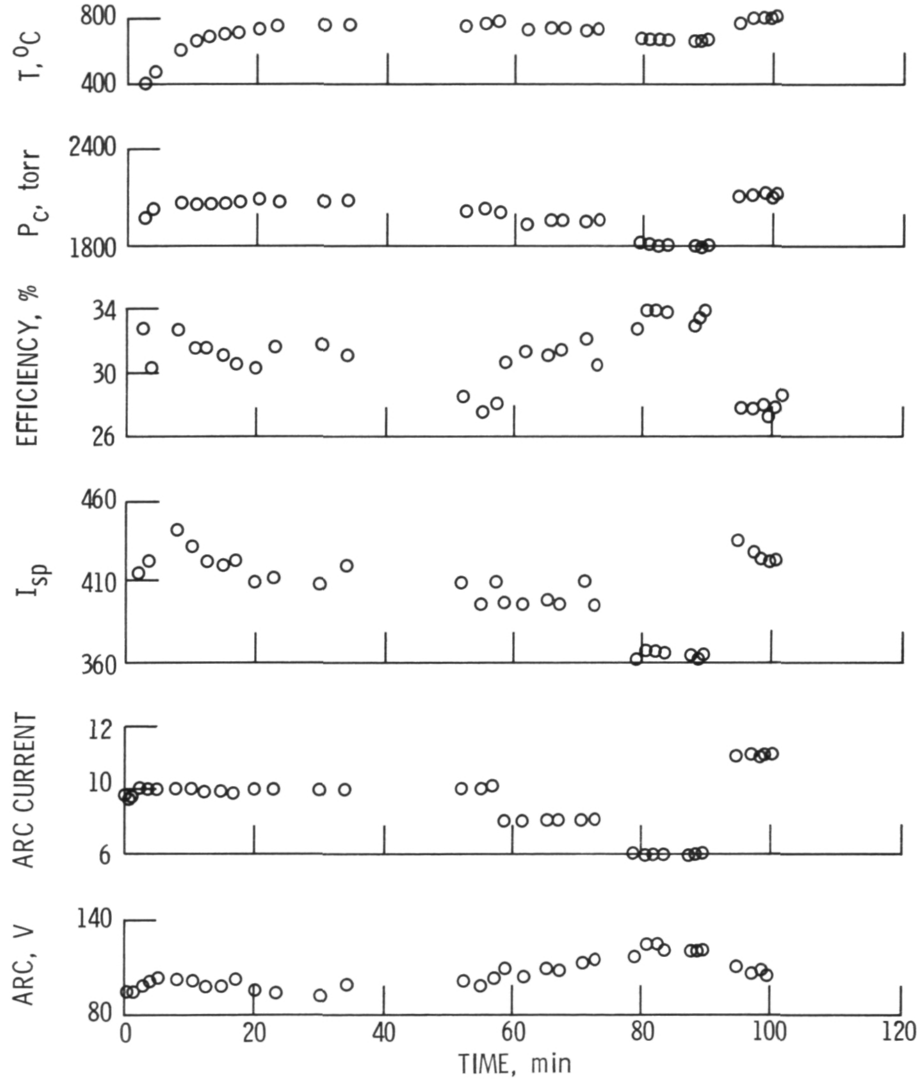


Figure 14. - Various parameters versus time for extended tests.

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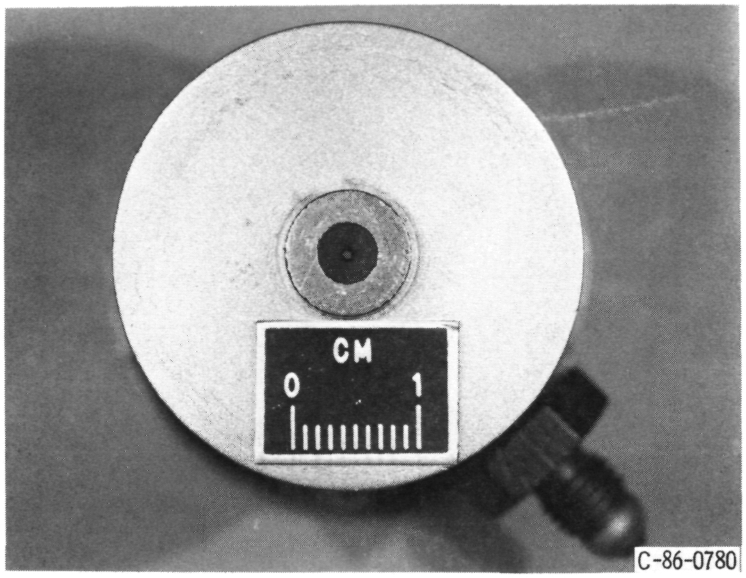
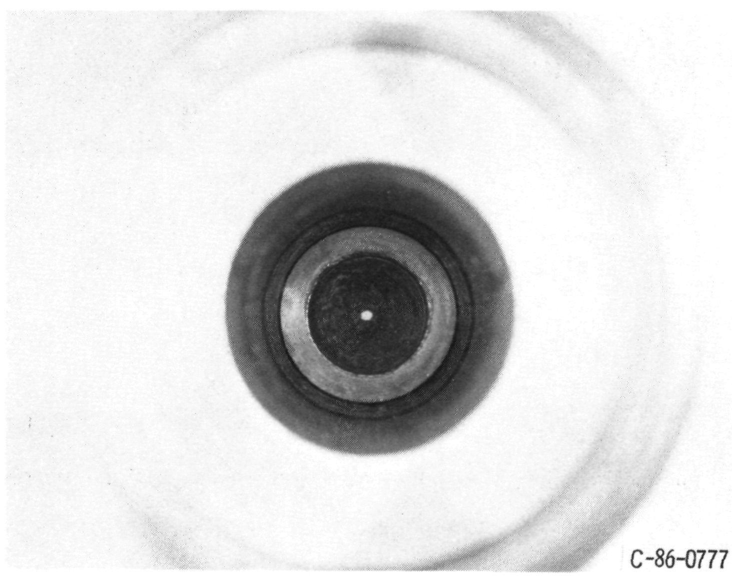


(a) Diverging side of nozzle insert; post-test.



(b) Converging side of nozzle insert; post-test.

Figure 15.

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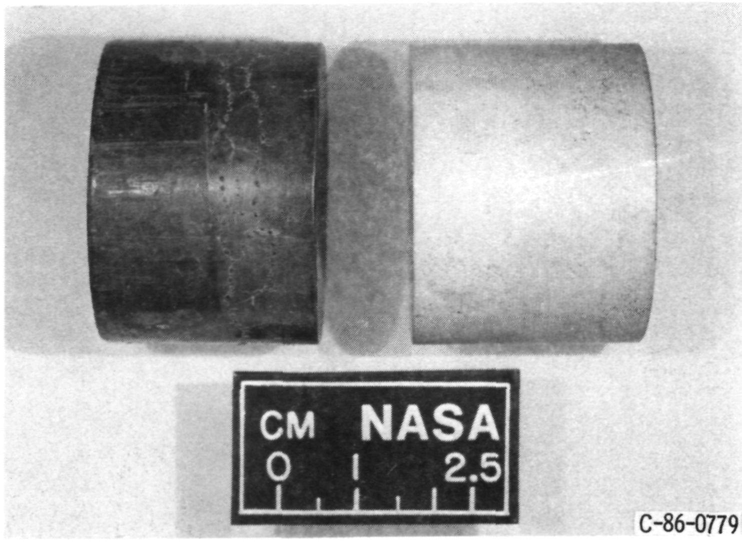
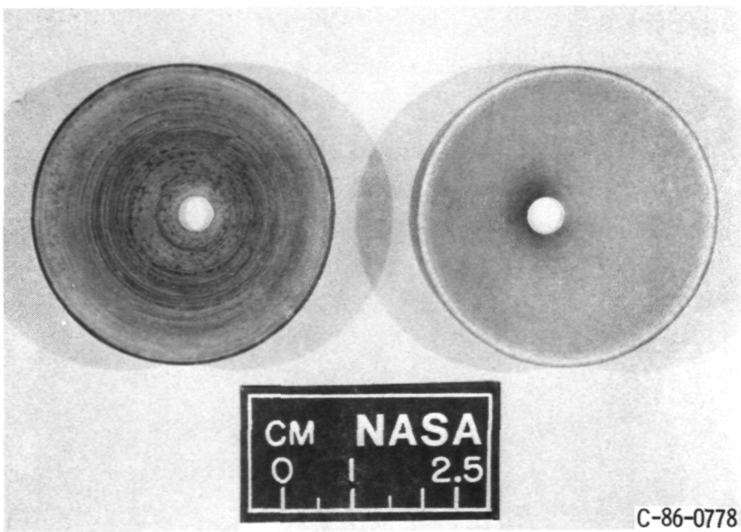


(a) HBN (left) and HBR (right) grade nozzle extensions. (Side view)



(b) HBN (left) and HBR (right) grade nozzle extensions. (View into nozzle)

Figure 16.

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16. Abstract
The arcjet assembly from a flight model system was modified with a new thoriated tungsten nozzle insert and has been tested with hydrogen-nitrogen mixtures simulating the decomposition products of ammonia and hydrazine. Arcjet power consumption ranged from 0.7 to 1.15 kW depending on low rate, input current, and mixture composition. At a nominal 1 kW power level the ammonia mixtures thrust efficiency was about 0.31 at specific impulse values ranging between 460 and 500 sec. Hydrazine mixtures gave similar thrust efficiencies at the same power level with specific impulse values between 395 and 430 sec. Large, spontaneous voltage mode changes were not observed once the thruster had passed a period of instability immediately following start up. This period of instability, and the startup at low pressure, were seen as major causes of constrictor damage during the tests.

17. Key Words (Suggested by Author(s))
Auxiliary propulsion; Arcjets; Nozzle effects; Vortex flow; Storable propellants

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